Integrating Atmospheric Conditions into the Dynamic-Arrival-Routes Framework

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Introduction

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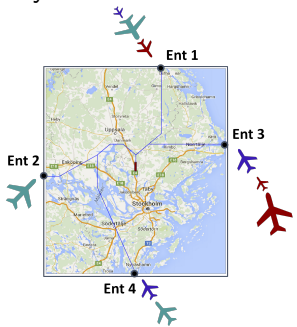
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- Need for automated sequencing + environmentally friendly descents
- Dynamic Arrival Routes (DARs):
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- Arrival routes make a tree
  - Root = Runway
  - Leaves = Entries



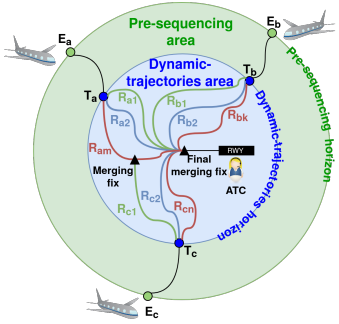
Concept of Operations

and

Problem Description

Concept of Operations[1]

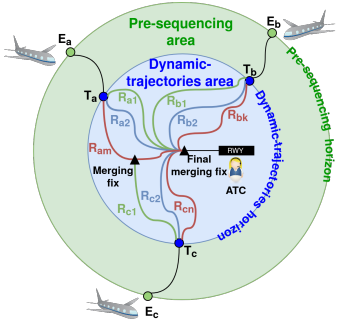
- Aircraft arriving to E-TMA (E_a, E_b, E_c)



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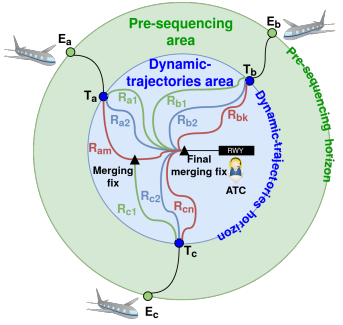
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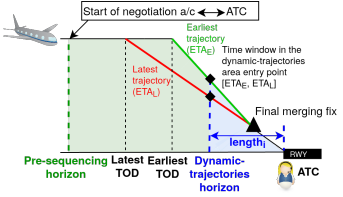


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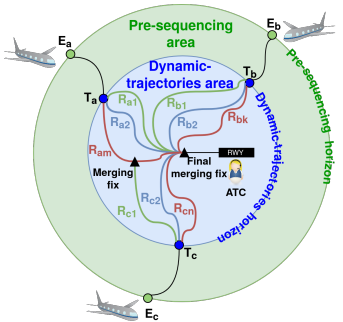




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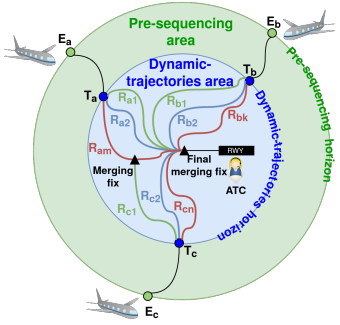
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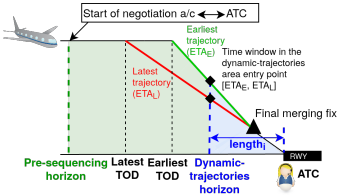


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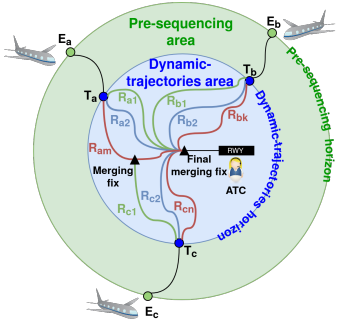


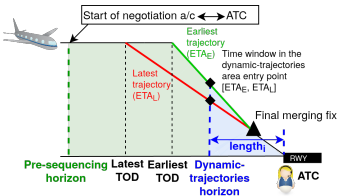


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- Goal: a/c know RTA + arrival tree at TMA entry point
- a/c ↔ ATCO communication before E-TMA
- Enough time for computations





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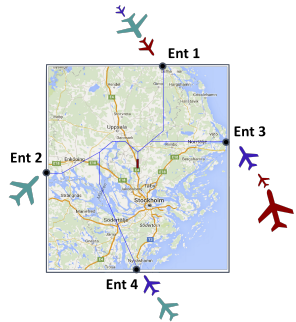
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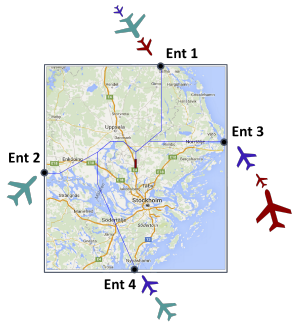
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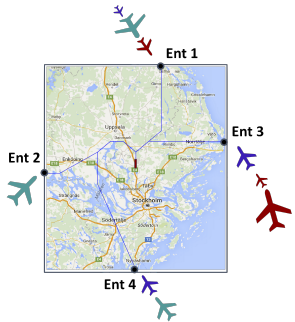
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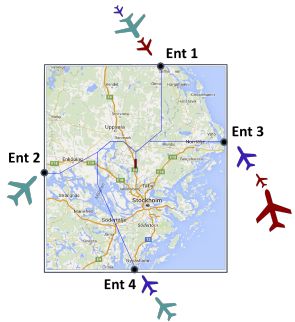
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5. Flexible entry times
6. Temporal separation with different wake turbulence categories
7. Following energy efficient descent profiles (CDO)



Objective



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- Minimize the total distance covered by all aircraft in the TMA



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- Minimize the area occupied by the tree



Objective

- Minimize the total distance covered by all aircraft in the TMA
- Minimize the area occupied by the tree
- Combination of both



Challenges in Previous Approach

- MIP-based DARs model had very long runtimes (up to 40+ hours)
- Based on only path-length descent profiles
- Could not incorporate atmospheric conditions or departure interactions
- Therefore, we reformulated (Dantzig-Wolfe reformulation) the entire problem[2]
- Now we have a path-based model that is significantly faster and supports realistic operational features

[2] R. Hajizadeh, T. Polishchuk, E. Rönnberg, and C. Schmidt, "A Dantzig-Wolfe reformulation for automated aircraft arrival routing and scheduling", 2025. [Online]. Available: https://arxiv.org/abs/2509.13065

Our Contributions

- Integrating atmospheric conditions into descent profiles
- Handling interaction with standard instrument departure routes (SIDs)
- Proof-of-concept results for Stockholm Arlanda

Path-Based Model: Key Ideas

- Grid discretization of the TMA
- Discretization of the time
- Enumeration of all possible paths from each entry point to the runway
- Precomputed descent profiles tied to each path
- Ensures all operational requirement

$$\min \quad \beta \sum_{(i,j)\in E} l_{i,j} x_{i,j} + (1-\beta) \sum_{k\in\mathcal{P}} \sum_{r\in\Pi_k} \sum_{(i,j)\in\theta_{kr}} |A_k| l_{i,j} \rho_{kr} \tag{1}$$

$$\text{s.t.} \quad \sum_{j:(i,j)\in E} x_{i,j} \le 2, \qquad \forall i \in V \setminus \{\mathcal{P} \cup r\}, \tag{2}$$

$$\sum_{j:(i,j)\in E} x_{i,j} \le 1, \qquad \forall i \in V \setminus \{\mathcal{P} \cup r\}, \tag{3}$$

$$x_{i,i+1+n} + x_{i+1+n,i} + x_{i+n,i+1} + x_{i+1,i+n} \le 1 \qquad \forall i \in V' \setminus \{\mathcal{P} \cup r\} : i+1+n, i+n, i+1 \notin \{\mathcal{P} \cup r\}, \tag{4}$$

$$x_{i,i+1+n} + x_{i+n,i+1} + x_{i+1,i+n} \le 1, \qquad \forall i \in \mathcal{P} \cap V', \tag{5}$$

$$x_{i,i+1+n} + x_{i+1+n,i} + x_{i+1,i+n} \le 1, \qquad \forall i : i+1 \in \mathcal{P}, \tag{6}$$

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$$x_{i+1+n,i} + x_{i+n,i+1} + x_{i+1,i+n} \le 1, \qquad \forall i : i+n+1 \in \mathcal{P}, \tag{8}$$

$$\sum_{s\in\Omega_k} \rho_{ks} = 1, \qquad \forall k \in \mathcal{P}, \tag{9}$$

$$\rho_{kr} \le x_{i,j}, \qquad \forall r \in \mathbf{\Pi}, \forall (i,j) \in \theta_{kr}, \tag{10}$$

$$\sum_{s\in\Omega_k} \sum_{t=\mathcal{E}_{k,r}-\mu}^{\mathcal{E}_{k,r}+\mu} \tau_{ks,t} = 1, \qquad \forall k \in \mathcal{P}, \forall a \in \mathcal{A}_k, \tag{11}$$

$$\sum_{t=\mathcal{E}_{k,r}-\mu}^{\mathcal{E}_{k,r}+\mu} \tau_{a,r,t} = \rho_{kr}, \qquad \forall k \in \mathcal{P}, \forall a \in \mathcal{A}_k, \forall r \in \Pi_k, \tag{12}$$

$$\sum_{k\in\mathcal{P}} \sum_{a\in\mathcal{A}_k \cap C_{a_2}} \sum_{t'=\tau-\mu}^{\tau} \sum_{\tau\in\overline{\tau}_{a_1,t_1-t',a_2}} \tau_{a,a,k_a+t'} \le \Omega(1 - \sum_{k\in\mathcal{P}} \sum_{a'\in\mathcal{A}_k \cap C_{a_1}} \sum_{t'=\tau-\mu}^{\tau} \sum_{\tau'\in\overline{\tau}_{a',t_1-t'}} \tau_{a',a',k_{a'}+t'}),$$
$$\forall a_1, a_2 \in \mathcal{C} : a_1 \ne a_2, \forall i \in V, \forall t \in \{0,\dots,\overline{\tau} - \sigma_{a_1,a_2} + 1\}, \tag{13}$$

$$\sum_{k\in\mathcal{P}} \sum_{a\in\mathcal{A}_k \cap C_{a_2}} \sum_{a'\in\mathcal{A}_{k'} \cap C_{a_1}} \sum_{t'=\tau-\mu}^{\tau} \sum_{\tau\in\overline{\tau}_{a_2,t_2-t',a_1}} \tau_{a,a,k_a+t'} \le \Omega(1 - \sum_{t'=\tau-\mu}^{\tau} \sum_{\tau'\in\overline{\tau}_{a',t_1-t'}} \tau_{a',a',k_{a'}+t'}),$$
$$\forall a_1 \in \mathcal{C}, \forall a' \in C_{a_1}, \forall i \in V, \forall t \in \{0,\dots,\overline{\tau} - \sigma_{a_1,a} + 1\}, \tag{14}$$

$$x_{i,j} \quad \text{binary}, \qquad \forall (i,j) \in E, \tag{15}$$

$$\rho_{kr} \quad \text{binary}, \qquad \forall r \in \mathbf{\Pi}, \tag{16}$$

$$\tau_{a,r,t} \quad \text{binary}, \qquad \forall k \in \mathcal{P}, \forall a \in \mathcal{A}_k, \forall t \in [l_a - \mu, l_a + \mu]. \tag{17}$$

Computation of Descent Profiles

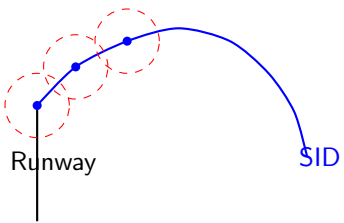
Descent Profile Computation

- Aircraft performance: BADA v.4 model (thrust, drag, fuel flow, speed schedules)
- Total Energy Model: backward integration from runway to entry point
- Speed handling: initial CAS/Mach estimated from ADS–B, then follow BADA's altitude-dependent schedule
- Atmospheric conditions: wind and temperature from ERA5
- Path-dependent trajectories: each feasible path has its own descent profile
- Parallelizable: profiles for different aircraft and paths computed independently

Taking Departures into Account

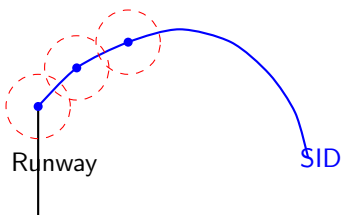
Integrating Departures (SIDs)

- Arrival routes must avoid conflicts with departing aircraft on SIDs



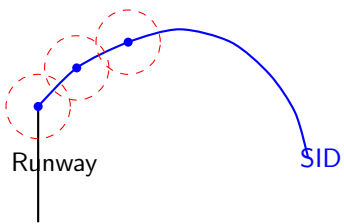
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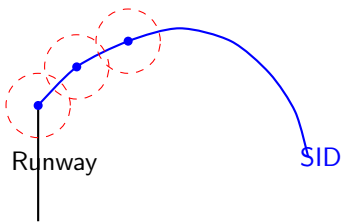
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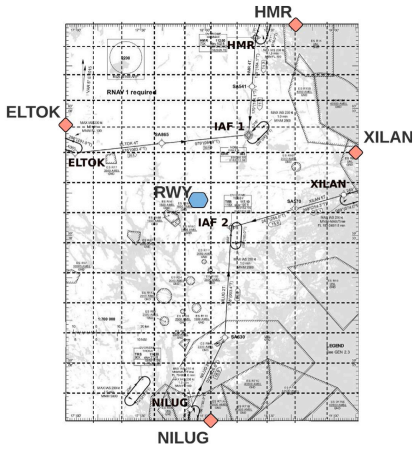
- Arrival routes must avoid conflicts with departing aircraft on SIDs
- Let d be the distance threshold and $\mathcal{D}$ the minimum separation distance
- For each SID, select points within along-route distance d from the runway
- Exclude grid nodes within separation distance D from these points



Experiments

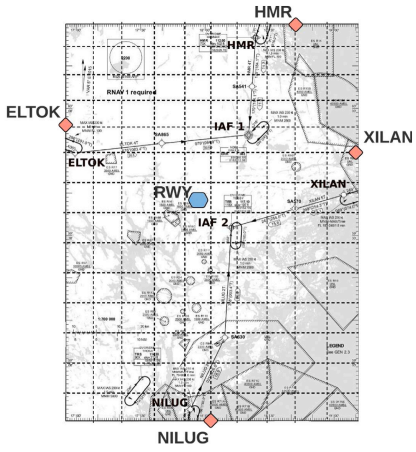
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- Arlanda airport with a 15×11 grid (separation of 6 NM)



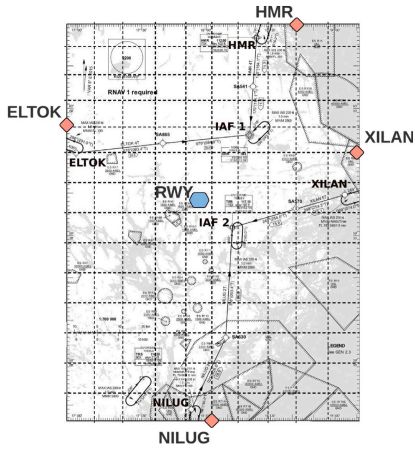
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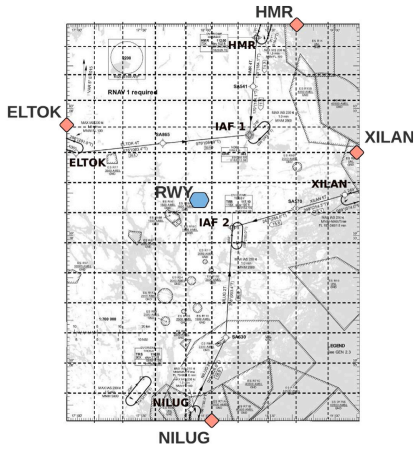
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- For integration with departure routes: from 5:00 to 5:29 AM including 16 aircraft (6 light)



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- For integration with departure routes:
  - Upper bound on the number of edges of a path = 14
- Path generation $<$ 1s

Computation Times

- With atmospheric conditions:
  - 1210 descent profiles needed
  - Computation time: ≈ 25 seconds per profile
  - Sequential generation would take > 8 hours
  - But fully **parallelizable** across aircraft and paths

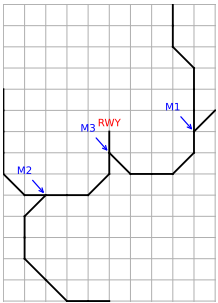
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- Without atmospheric conditions (length-based profiles):
  - Only 56 profiles required (by route length)
  - Computation time: a few seconds per profile

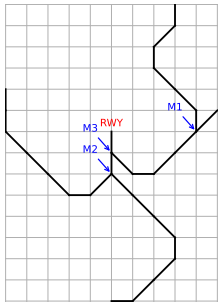
Computation Times

- With atmospheric conditions:
  - 1210 descent profiles needed
  - Computation time: ≈ 25 seconds per profile
  - Sequential generation would take > 8 hours
  - But fully **parallelizable** across aircraft and paths
- Without atmospheric conditions (length-based profiles):
  - Only 56 profiles required (by route length)
  - Computation time: a few seconds per profile
- MET-based profiles are computationally heavy, but once generated, the optimization runs in under a second

Optimal Arrival Trees with and without MET



Without MET

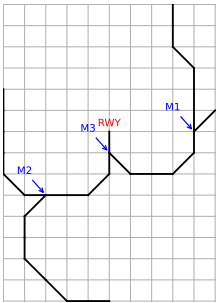


With MET

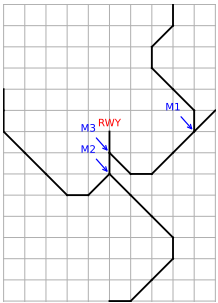
1-minute discretization

Fixed entry times

Optimal Arrival Trees with and without MET



Without MET



With MET

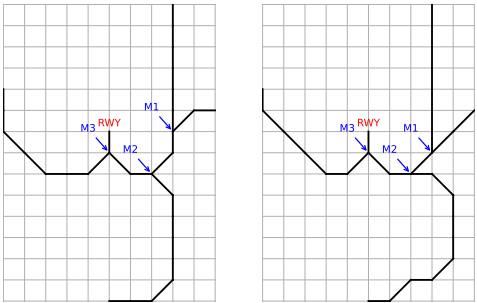
	Without MET	With MET
Objective value	80.13	75.14
Tree weight	33.73	33.63
Total paths length	85.28	80.50
Total runtime (s)	1.28	0.43
Av. time in TMA (min)	17.71	16

Time to generate all trajectories < 1 second

1-minute discretization

Fixed entry times

Refined Time Discretization

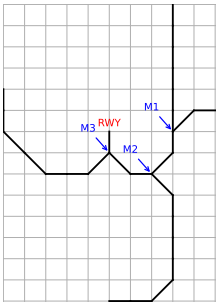


Without MET With MET

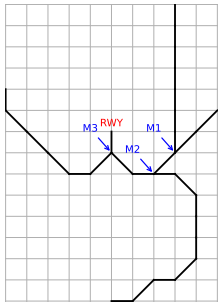
30-second discretization

Entry point time-window offset = 1

Refined Time Discretization



Without MET



With MET

	Without MET	With MET
Objective value	70.14	69.96
Tree weight	31.31	32.56
Total paths length	74.45	74.11
Total runtime (s)	3.4	0.67
Av. time in TMA (min)	13.64	14.36

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30-second discretization

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Result Comparison

1-minute discretization:

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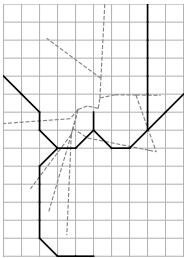
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30-second discretization:

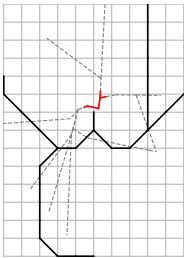
	Without MET	With MET
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Tree weight	31.31	32.56
Total paths length	74.45	74.11
Total runtime (s)	3.4	0.67
Av. time in TMA (min)	13.64	14.36

30-second discretization gives better solution than 1-minute discretization

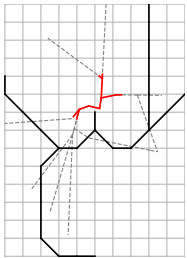
Optimal Arrival with Consideration of SIDs



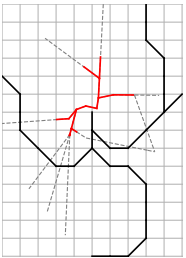
$d = 0$ NM



$d = 6$ NM

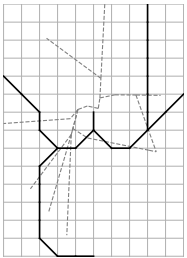


$d = 12$ NM

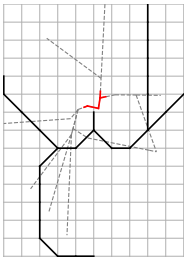


$d = 18$ NM

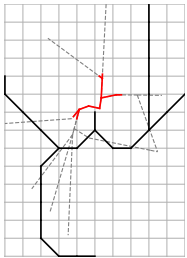
Optimal Arrival with Consideration of SIDs



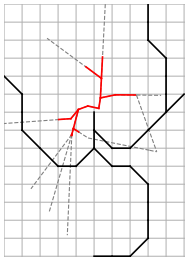
$d = 0$ NM



$d = 6$ NM



$d = 12$ NM



$d = 18$ NM

	$d = 0, 6, 12$	$d = 18$	$d \geq 24$
Objective value	149.03	162.04	
Tree weight	31.14	33.97	
Total paths length	162.13	176.27	Infeasible
Total runtime (s)	56–64	26.77	
Av. time in TMA (min)	13.5	14.37	

Entry point time-window offset = 2
Time to generate all trajectories: 8 to 18.13 seconds

Conclusion

Conclusion and Future Work

- Framework integrates MET conditions and SID interaction

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Using finer time resolution? $\Big)$ $\Longrightarrow$ Column generation
- Current SID exclusion method conservative

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- $\left.\begin{array}{l}\text{Using finer grid?}\\ \text{Using finer time resolution?}\end{array}\right) \Longrightarrow$ Column generation
- Current SID exclusion method conservative $\Longrightarrow$ take vertical separation into account

Conclusion and Future Work

- Framework integrates MET conditions and SID interaction
- Short runtimes make real-world use feasible
- DARs become more realistic and environmentally beneficial

Thank You!

- Using finer grid?
  Using finer time resolution? $\Longrightarrow$ Column generation
- Current SID exclusion method conservative $\Longrightarrow$ take vertical separation into account